A&A manuscript no.
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08.09.2; 09.01.1

ASTRONOMY
AND
ASTROPHYSICS
1.2.2008

A very reduced upper limit on the interstellar abundance of beryllium.*

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Received January 22, accepted February 25, 1997

Abstract. We present the results of observations of the λ3130.4Å interstellar absorption line of ^{9}Be II in the direction of ζ Per. The data were obtained at the Canada-France-Hawaii 3.6m Telescope using the Coudé f/4 Gecko spectrograph at a resolving power $\lambda/\Delta\lambda \simeq 1.1 \times 10^5$, and a signal-to-noise ratio S/N $\simeq$ 2000. The ^{9}Be II line is not detected, and we obtain an upper limit on the equivalent width $W_{3130.4} \leq 30\ \mu$Å. This upper limit is 7 times below the lowest upper limit ever reported hitherto. The derived interstellar abundance is $(^9\mathrm{Be/H}) \leq 7 \times 10^{-13}$, not corrected for the depletion of ^{9}Be onto interstellar grains; it corresponds to an upper limit $\delta_{Be} \leq -1.5$ dex on the depletion factor of ^{9}Be. As such, it argues in favour of models of formation of dust grains in stellar atmospheres.

Key words: ISM: abundances – Stars: individual: ζ Per

1. Introduction

Beryllium is created in Big Bang nucleosynthesis (BBN) with an extremely low primordial abundance, $(^9\mathrm{Be/H})_p < 10^{-14}$. Subsequently, it is solely formed in spallation reactions of galactic cosmic rays (GCR) interacting with interstellar C, N, O atoms, and is thoroughly destroyed through astration of interstellar gas. This simple scenario allows to account for the observed Pop I abundance of ^{9}Be, $(^9\mathrm{Be/H})_{PopI} \simeq 1.3 \times 10^{-11}$ (Boesgaard 1976), the solar abundance $(^9\mathrm{Be/H})_\odot \simeq 1.4 \times 10^{-11}$ (Chmielewski et al. 1975) and the meteoritic abundance $(^9\mathrm{Be/H})_{met} \simeq 2.6 \times 10^{-11}$ (Anders & Grevesse 1989). For this reason, ^{9}Be together with ^{6}Li, which shares a similar evolutionary picture, are used as tracers of cosmic ray spallation activity.

For our present purpose, the main importance of the interstellar abundance of ^{9}Be is related to the physics of formation of dust grains, through the depletion factor of ^{9}Be, δ_{Be} (Snow et al. 1979). Field (1974) observed a correlation between the underabundance of an element in the interstellar medium (ISM) and the condensation temperature of that element, defined as the threshold at which half of the gaseous phase has gone to solid state; this suggests that dust grains were formed under equilibrium pressure in late-type giants atmospheres or stellar nebulae. On the other hand, Snow (1975), noticing a similar correlation trend between the depletion factors of chemical elements and their first ionization potentials (except for three elements), suggested that dust grains were formed by collisions in the ISM. In this case, depletion should increase with time, elements should be selectively depleted (*i.e.* the element-to-element depletion ratio should vary from one line of sight to another and the amount of depletion should depend on the cloud density. Similar conclusions have been subsequently reached by Barlow (1978), and Duley & Millar (1978). This situation is not settled as yet, since many more observations have revealed that: (i) depletions effectively vary from sightline to sightline; (ii) but there is no evidence of element-to-element depletions ratio variation (Joseph 1988, and references therein). As well, it has been shown that the condensation temperature may not always be a good indicator of depletion, most notably with respect to the phosphorus/iron ratio of depletion (Jura & York 1978). Note that in the above presentation and all throughout the paper, we only refer to rather diffuse clouds, and not to denser clouds. In effect, depletion within cloud discussed here could be quite different from the denser ones in which the material is probably protected from grain-disrupting shocks and the density high enough to initiate species-specific depletion mechanisms.

Beryllium presents the advantage of being a clear element discriminator of these various approaches. Its depletion factor is predicted to be $\simeq -0.2$ dex in a correlation with first ionization potential, and $\simeq -1.5$ dex in

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* Based on observations collected at the Canada-France-Hawaii Telescope, Hawaii, USA.

a correlation with condensation temperature (Snow et al. 1979; Boesgaard 1985). However, ^{9}Be has never been detected in the ISM so that, its actual depletion factor is largely unknown.

Here, we report on our observations of the λ3130.4Å interstellar absorption line of ^{9}Be II in the direction of ζ Per. Previous unsuccessful attempts are discussed in Sec.2, together with our observations; their analysis are discussed in Sec.3, and their results in Sec.4.

2. Observations.

No firm detection of ^{9}Be has ever been reported in the ISM because of the extreme difficulty of this observation. ^{9}Be II, the dominant ionization stage of ^{9}Be in the ISM (the first ionization potential of ^{9}Be is 9.3 eV, and the second 18.2 eV), can only be observed through the resonance doublet at λ3130.420/3131.066Å, *i.e.* in the near–ultraviolet where the atmospheric absorption is important. On the basis of the cosmic abundance of ^{9}Be, $(^9\mathrm{Be/H})_{cosm} \simeq (^9\mathrm{Be/H})_{met} \simeq 2.6 \times 10^{-11}$ [$(^9\mathrm{Be/H})_{cosm} \neq (^9\mathrm{Be/H})_{\odot}$ cause of the depletion of ^{9}Be by nuclear reactions at the bottom of the convection zone of the Sun (Anders & Grevesse 1989)], the hydrogen column density toward ζ Per, N(H)=1.6×10^{21} cm^{-2} (Savage et al. 1977), and a depletion factor δ_{Be} between -0.1 and -2.0 dex, one should expect a column density N(Be II) ranging from 3×10^{10} to 4×10^{8} cm^{-2}, hence an equivalent width $W_{3130.4}$ from 900 to 10 μÅ. In this optically thin case, we obtain the column density N (in cm^{-2}) from the equivalent width W (in Å) by the expression:

$$N = 1.13 \times 10^{20} \frac{W}{\lambda^2 f},$$

where f is the oscillator strength and λ the wavelength (in Å). The upper limits to the equivalent widths of interstellar ^{9}Be that have been reported up to now are listed in Table 1.

Our observations were conducted in January 1994 and October 1995 at the Canada–France–Hawaii Telescope, whose altitude (4200 m) allows for a good UV transparency. We used the spectrograph Coudé f/4 Gecko at high resolving power $R \simeq 1.1 \times 10^5$ (equivalently 0.029 Å, 2.8 km.s^{-1}, or 2.8 pixels). This spectrograph carries a Richardson image slicer. The detector is a 2K CCD with a pixel size of 15 μm. Its quantum efficiency is about 0.7 at 3100 Å. We took care during the observations to shift the central wavelength from night to night in order to identify eventual systematic features on the CCD detector. As well, thorium-argon lamp calibration exposures were recorded each night, interspaced with stellar exposures, in order to achieve as high a level of wavelenght accuracy as possible. This is necessary in that one goes blind looking for a line that may appear only after all individual spectra have been correctly shifted and properly averaged. Over the six observing nights, calibration root mean square range between 1 and 2 mÅ (*i.e.* between $1/10^{th}$ and $1/5^{th}$ of a pixel). Flat fields were performed on a platinum lamp at the beginning and the end of night in order to obtain a very high level flat field while optimizing the integration time spent on ζ Per.

3. Data reduction and analysis.

The data were reduced using the IRAF and MIDAS softwares. It was found that scattered light is present in the spectrograph at a non-negligible level. Moreover, due to the presence of a cross-disperser (which projects different spectra from different orders perpendicularly to the dispersion) and to the small inter-order spacing in the near-UV, there resulted a slight overlap of the scattered light with observing adjacent orders at the time of the first run. This overlap was not present during the second run because of a better adjusting of the spectrograph. Even when there is an overlap, the scattered light could nonetheless be interpolated, and the remaining background level after removal did not exceed $\simeq 1\%$ in all CCD frames, so that the zero flux level should be precisely known.

It proved difficult to flat-field the spectra because of the image slicer device. In effect, the 5 slices of signal are here reconstructed one on top of another on the CCD, instead of being spread out perpendicularly to the dispersion. We noticed that the signal on the CCD was not uniform, meaning that probably the reconstruction is not perfect. However, this non-uniformity of the signal might also be due to a non-perfect focussing of the four separate grating of the mosaic. As a result, a non-negligible part of the image on the CCD typically had to be dropped off before flat-fielding and averaging to a single spectrum, in order to preserve a precise flat-fielding. Before co-adding the different spectra (about fifty of typically 30-45 min integration time each), each spectrum was corrected to the heliocentric rest frame. Different statistical filters for co-addition were applied to different set of spectra, and at the end, the average spectrum showing the highest signal-to-noise ratio in the vicinity of λ3130Å was kept.

The aspect of the average normalized spectrum of ζ Per in the λ3130Å region is shown in Fig.1. An enlargement of the final spectrum around the ^{9}Be II line is shown in Fig.2 where 1σ error bars are also plotted. It is the weighted average of 44 individual spectra, for a total integration time of 25 h. We reach a signal-to-noise ratio of $\simeq$ 2000 per pixel in the vicinity of the expected line (S/N $\simeq$ 3000 per resolution element).

Only one absorption line in the spectrum of Fig.1 is identified: the CH line at 3137.53 Å (oscillator strength $f = 1.2 \times 10^{-3}$, Chaffee & Lutz 1977) measured at 3137.706 ± 0.006 Å, *i.e.* at a heliocentric radial velocity of 16.8 ± 0.6 km.s^{-1}. The Gaussian full width at half maximum (FWHM) for this line is 38 ± 8 mÅ, and the equivalent width $2.0{\pm}0.2$ mÅ, corresponding to a column density of $1.9 \pm 0.2 \times 10^{13}$ cm^{-2} (optically thin line). During the

Table 1. Previous attempts at detecting interstellar ^{9}Be and upper limits derived. These abundances are not corrected for the depletion of ^{9}Be onto dust grains.

Authors	Targets	Equivalent widths	Abundances
Herbig (1968)	ζ Oph	< 2.5 mÅ	$< 1.4 \times 10^{-11}$
Boesgaard (1974)	22 stars		$< 5 \times 10^{-11}$
Chaffee & Lutz (1977)	ζ Per	< 0.6 mÅ	$< 1.3 \times 10^{-11}$
York, Meneguzzi & Snow (1982)	ζ Oph	< 1 mÅ	$< 2 \times 10^{-11}$
York, Meneguzzi & Snow (1982)	σ Sco	< 1 mÅ	$< 1.3 \times 10^{-11}$
Boesgaard (1985)	ζ Per	< 0.23 mÅ	$< 4.8 \times 10^{-12}$
Boesgaard (1985)	δ Sco	< 0.36 mÅ	$< 8.4 \times 10^{-12}$
Baade & Crane (1991)	ζ Oph	< 0.3 mÅ	$< 6 \times 10^{-12}$
This work	ζ Per	< 0.03 mÅ	$< 7 \times 10^{-13}$

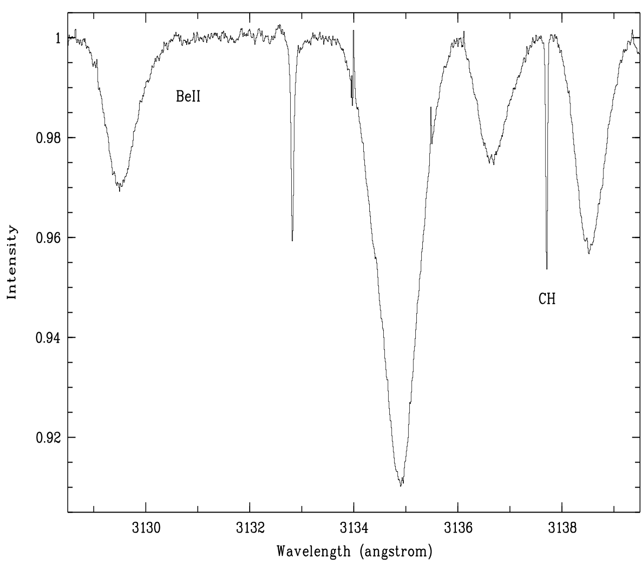

Fig. 1. Spectrum of ζ Per. The resolving power is $\lambda/\Delta\lambda \simeq 1.1 \times 10^{5}$. The ^{9}Be II doublet is expected at 3130.6 Å and 3131.2 Å.

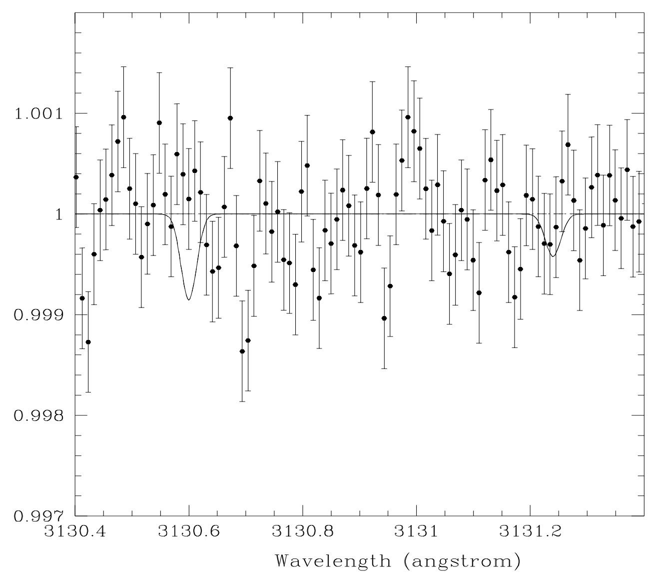

Fig. 2. Final spectrum of ζ Per enlarged where the the ^{9}Be doublet is expected. Solid line corresponds to the limiting 30 μÅ detectable equivalent width at 3σ (see text).

first run another CH line at 3143.15 Å was observed with an equivalent width of 5.9 ± 0.6 mÅ corresponding exactly to the f ratio between the two CH lines.

The widths of the 4 broad spectral features are $\gtrsim$ 65 km.s^{-1}, in agreement with the stellar rotational velocity $v.sini = 60$ km.s^{-1}, confirming their photospheric origin. The absorption line near 3133 Å is puzzling. Since its position has shifted by $\simeq$ 0.4 Å (*i.e.* $\simeq$ 40 km.s^{-1}) between the two observing runs, its origin could be instrumental.

The radial velocity of the interstellar CH line found here at $\simeq$ 16.8 km.s^{-1} differs slightly from previous measurements with different atomic or ionic lines at 14 km.s^{-1} (see *e.g.* Hobbs 1978 or Welty et al. 1994 and 1996). Nevertheless, the difference is within the instrumental resolutions.

We have searched for the ^{9}Be II lines at these two velocities. Whatever the velocity is, the detection is not convincing. However, the absence of detection at such a high signal-to-noise ratio and resolution translates into a very reduced upper limit on the beryllium column density.

To obtain this upper limit, we considered that the strongest ^{9}Be line at 3130.420 Å has the same FWHM as the CH line. We assume that it has a depth $\lesssim 0.1\%$ (the standard deviation of the pixel's value in this spectral region is $\simeq \pm 0.05\%$). The Gaussian gives then an equivalent width of about 30 μÅ. In effect, the limiting detectable equivalent width W_{lim} at 3σ is given by $W_{lim} \equiv \frac{3\Delta\lambda}{S/N}$.

With our S/N per resolution element $\Delta\lambda$ of $\simeq 3000$, we obtain $W_{lim} \simeq 30\,\mu$Å.

We can then deduce an upper limit on the column density. In this optically thin case, we obtain $N(^9\mathrm{Be\,II}) \simeq 1.0 \times 10^9$ cm^{-2} ($f = 0.3382$ for this line, Morton 1991). The spectrocopic data related to these two lines are known from theoretical calculations. These lines were already detected in stars revealing no discrepancies with respect to their f-values. The absorptions corresponding to this column density are shown as solid line in Fig.2 at a radial velocity of 16.8 km.s^{-1} (the result is similar for a radial velocity of 14 km.s^{-1}).

We assume now that at least 90% of the interstellar beryllium is present in the first ionization stage ^{9}Be II (Boesgaard 1985). This is supported by the ratios between ionization stages of others elements. For example, in this same line of sight, $N(\mathrm{Mg\,I})/N(\mathrm{Mg\,II}) \leq 10^{-2}$ and $N(\mathrm{S\,III})/N(\mathrm{S\,II}) \leq 10^{-3}$ (Snow 1977). Taking the hydrogen column density toward ζ Per $N(\mathrm{H}) = 1.6 \times 10^{21}$ cm^{-2} (Savage et al. 1977), we thus deduce an upper limit of the interstellar abundance for ^{9}Be toward ζ Per:

$$(^9\mathrm{Be/H})_{\zeta\,Per} \leq 7 \times 10^{-13}\ .$$

This abundance is not corrected for ^{9}Be depletion onto dust grains.

4. Discussion and conclusions.

Our interstellar abundance of ^{9}Be is at least 35 times less than the cosmic abundance, $(^9\mathrm{Be/H})_{cosm} \simeq 2.6 \times 10^{-11}$. It corresponds to a depletion factor $\delta_{Be} \leq -1.5$ dex. This is a new and much more stringent upper limit compared to previous ones ($\delta_{Be} \leq -0.4$, Boesgaard 1985).

As explained in Sec.1, our present upper limit largely favours the Field (1974) model of dust grain formation in stellar material. In effect, the predicted depletion for the condensation temperature of ^{9}Be ($\simeq$ 1250 K) is $\simeq -1.5$ dex while the Snow (1975) model of dust grain formation by chemical trapping predicts $\delta_{Be} \simeq -0.2$ dex.

As already said, the observed absence of selective depletions among chemical elements on different sightlines (Joseph 1988) argues also against the model of Snow (1975).

However, the condensation temperature curve might not always be a good indicator of depletion, since, for instance, P is always ten times less depleted than Fe although they have the same condensation temperature (Jura & York 1978). This may be reconciled with the model of Field (1974), if one takes into account the blocking of P depletion in stellar atmospheres through the formation of stable molecules (*e.g.* PN), which would later dissociate in the ISM (Gail & Sedlmayr 1986). Still, Joseph (1988) has shown evidence of a physical process acting on grains in the ISM, since the overall level of depletion is found to vary from line of sight to line of sight. Joseph (1988) proposes that dust grains are indeed formed in a first stage in stellar material, where the element-to-element depletion ratios are reproduced; in a second stage, grain destruction in passing shock fronts would account for the overall variation of depletion. In order to preserve the observed constancy of the element-to-element depletion ratio, Joseph (1988) argues that the most depleted elements are locked in grain cores, mainly Fe, Si, Ca, and the less depleted are trapped in the mantles, mainly P, Mg, S. These nonvolatile mantles could form in the aftermaths of shocks, and hence protect the grain core from destruction.

Beryllium fits in this scenario: ^{9}Be II as Mg II is one valence, Be, Mg and P have similar condensation temperatures, and furthermore, Be and P have similar first ionization potentials. One should therefore expect to find beryllium trapped in the grain mantles, and to observe a strong correlation of the depletion factors of these elements on various lines of sight. Our upper limit $\delta_{Be} \leq -1.5$ is indeed in agreement with the depletion factor $\delta_{Mg} \simeq -1.3$ dex (Boesgaard 1985) on the same line of sight. Its discrepancy with the value $\delta_P \simeq -0.7$ dex (Boesgaard 1985) could then be associated with the abnormal P/Fe depletion ratio, *i.e.* with the undepletion of phosphorus in stellar atmospheres (see above). We can hope that a future detection of interstellar beryllium will not infirm this scenario since apparently we should not be far from an actual detection.

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